

AN ENVIRONMENTAL STUDY TO ASSESS THE IMPACT OF DRILLING
DISCHARGES IN THE MID-ATLANTIC. I. QUANTITY AND FATE OF DISCHARGES

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ABSTRACT

This report covers one facet of an environmental monitoring study on an offshore exploratory well in the Mid-Atlantic; of which the overall objective was to determine the effect of drilling discharges on ambient water quality, bottom sediments, and the benthic community. The environment was monitored around the well site before the rig moved on location (Pre-Drilling Phase), while the rig was on location (Drilling Phase), and after the rig moved off location (Post-Drilling Phase). This paper discussed the quantity, composition and immediate fate of drilling mud and formation drill solids discharged during the drilling phase. The results of two bulk mud discharge dispersion tests are also discussed.

The well was located approximately 156 km east of Atlantic City, New Jersey in an approximate water depth of 120 meters. The drilling phase of the program lasted from early January until mid-July 1979. During this time 752 metric tons of barite, 1,409 metric tons of low gravity solids (bentonite plus natural formation drill solids) and 94 metric tons of organic chemical (chrome lignosulfonate, lignite, and cellulose polymer) were discharged. Approximately 60-70% of these discharges were carried away from the rig in a south-south-westerly direction by the prevailing currents. The source of most trace metals in the discharges was the formation drill solids. Some mud additives contributed to chromium, zinc, and possibly lead concentrations in the discharges.

In the dispersion study water quality parameters (suspended solids, transmittance, dissolved oxygen, pH, temperature, and salinity) were measured during the two bulk mud discharge tests of 500 and 275 barrels per hour. Suspended solids and transmittance were the only two parameters affected by the discharges. In both tests suspended solids concentrations reached background levels before the plume had drifted 600 meters from the discharge source.

INTRODUCTION

During the drilling of offshore wells, it is necessary to periodically discharge drilling muds and natural formation drill solids to the ocean. The United States Environmental Protection Agency's Region II office requested that the Mid-Atlantic Operators conduct a monitoring study to measure environmental changes that occurred as a result of the drilling discharges. The joint study was carried out on one of Exxon USA's exploratory wells drilled in the Baltimore Canyon in the spring of 1979. Exxon administered the program for the operators and EG&G Environmental Consultants was the primary contractor.

The overall objective was to determine the effect of drilling discharges on ambient water quality, bottom sediments, and the benthic community. The study consisted of monitoring the environment around the well site before the rig moved on location (Pre-Drilling Phase), while the rig was on location (Drilling Phase), and after the rig moved off location (Post-Drilling Phase).

The pre- and post-drilling phases included hydrographic measurements, TV and still camera observations on the sea floor, and an extensive sediment and benthos sampling and analysis program. The nature and composition of the sediments were determined by grain size analysis and x-ray diffraction. Sediments were also analyzed for trace metals and extractable organics (oil and grease). The relative abundance and distribution of major benthic species were determined and animal tissue was analyzed for trace metals.

During the drilling phase, discharges were monitored both for quantity and composition. Ocean currents were also monitored throughout the drilling period. In addition, two bulk mud discharge tests were conducted to determine effects on water quality.

This paper discusses the quantity, composition and fate of mud and drill solids discharged during the drilling phase. In addition the results of the two bulk mud discharge dispersion tests are discussed. The benthic sampling design, trace metal analysis, and effects on the benthic community are discussed respectively by Robson et al. (1980), Mariani et al. (1980), and Menzie et al. (1980).

The study was conducted in NJ 18-3 Block 684 on the Mid-Atlantic Outer Continental Shelf (Figure 1). The block, which is leased to Exxon USA, is located approximately 156 km (97 miles) off the coast of New Jersey and has an approximate water depth of 120 meters. The well was located in the southwest sector of the block and centered at 39° 16' 45.48"N latitude and 72° 39' 10.24"W longitude. The Glomar Semi-I, a semisubmersible drilling rig, arrived at the well site on January 4, 1979 and moved off location on July 15, 1979.

METHODS

Monitoring Program

Discharges

During the entire drilling operation, whole mud discharges and solids control equipment (SCE) discards were sampled and analyzed. The solids control equipment aboard the Semi-I included three Milchem shale shakers, one DEMCO desander and two SWECO mud cleaners.

Whole mud samples were taken each time bulk muds were discharged, and SCE discard samples were taken twice a day from each piece of equipment when in use. Quantities and rates of discharge were measured at the time of sampling. Each sample was measured for mud density using a pressurized pycnometer. Solids composed of barite, low gravity solids (bentonite and drill solids) and organic chemical were determined by the combustion-gravimetric method involving simply a series of weighings after drying (at 100°C) and combusting (at 600°C). Drying the sample at 100°C evaporated the water from the sample. Firing (combusting) the dried sample at 600°C combusted the organic material and evaporated bound water in the clay. The remaining solids, after firing, included barite, low gravity solids (LGS), inorganic salts and organic ash.

The scheme for determining organic chemical, salt and solids content from the results of the combustion-gravimetric method is shown in Table 1. The salt content in whole mud samples was determined by measuring chlorides in the filtrate and using an empirically derived equation for conversion from chlorides to salt. The organic chemical factor, z , is a correction factor for the organic material combusted at 600°C, and was experimentally determined to be 0.83 for the specific organic chemicals used during the monitoring program. Also from experimental determinations, the weight loss of firing dried bentonite was found to be 5% and was used to correct the combustible organic chemical determination. Since the weight loss from drill solids on firing was not known, it was assumed that the weight loss for all low gravity solids (LGS) was the same as bentonite.

Along with the sampling analysis of the whole mud and SCE discard samples, the status (performance) of the solids control equipment was recorded daily. Also, records were kept of the material (barite, bentonite, etc.) added to the mud system.

Chemical analyses of barium and chromium in some solids samples were conducted to assist in interpreting results of the combustion-gravimetric method. Chromium determinations were made to estimate the organic chemical content in the discharges while barium determinations were made to calculate the percent barite in the solids. Consistently throughout the program the organic chemical content of the mud contained chrome lignosulfonate (48%), lignite (47%) and carboxymethyl cellulose (5%). 2.91% of the chrome lignosulfonate was chromium. Trace metal analyses (Cr, Cd, Pb, Hg, Ni, V and Zn) were also conducted on the major input material and some dried solids samples of mud and SCE discharges. The specific analytical techniques and their corresponding relative percent error for all the mineralogical and elemental determinations are presented in Table 2. X-ray diffraction, X-ray fluorescence and atomic absorption (AA) analyses were conducted by SCR Labs Inc., Houston. Total digestion procedures were used for preparation of AA samples. Atomic absorption analyses for trace metals on samples of muds

used in this dispersion study were carried out at the University of Delaware. In this case, samples were prepared by acid leaching. Uranium-West Labs, Los Angeles, performed the neutron activation analyses (Ellis and Chattotadahyay, 1979).

Currents

From January 20 to July 11, 1979, current speed and direction, and seawater temperature data were measured by internally recording instruments located inside the perimeter of anchor chains 500 meters southeast of the Semi-I. The near surface instrument, located at a depth of 10 meters, was a vector averaging current meter (VACM), producing 15-minute averages of current speed and direction to eliminate surface wave effects. Mid-depth and near bottom current meters located 69 and 117 meters deep, respectively, were of the Savonius rotor and vane type, and recorded every 20 minutes an average value of current speed and direction, plus seawater temperature.

Dispersion Tests

During the period April 20-22 dispersion tests were conducted to determine the effect of bulk mud discharges on water quality. Tests of 500 bbl/hr and 275 bbl/hr were conducted. During the 500 bbl/hr test 500 barrels of mud were discharged and during the 275 bbl/hr test 220 barrels of mud were discharged. Prior to these tests a 100 bbl/hr feasibility test was conducted using 100 barrels of mud. The composition of the muds used in the discharge tests is shown in Table 3.

The mud was released from the mud pits at a constant rate and shunted to a depth of 12 meters below the surface. The shunt pipe was 25.4 cm in diameter. Divers collected water samples within 15 meters of the discharge source using a meter tape attached to the discharge pipe and a depth gauge for position. Ten-liter Van Doren bottles were used to collect water samples in the plume near the discharge source. Plume sampling at distances greater than 70 meters from the discharge source was accomplished using hydrographic and water sampling equipment suspended from a helicopter. Details on the sampling equipment and procedure are discussed in Ayers et al. (1980).

RESULTS

The well was drilled to a depth of 4,970 meters from the seafloor. The casing program is shown in Table 4. The first 82 meters were drilled prior to setting the riser and taking returns to the rig. An estimated 460 barrels (190 metric tons) of drill solids were released on the ocean floor during this interval. It was impractical to take samples of this material, however, this part of the hole was drilled with seawater with no added chemicals.

Monitoring Program

Approximately 160 mud discharge samples and 200 SCE discard samples were analyzed. Amounts (bbls) of bulk mud and solids control equipment discharges versus time are presented in Figures 2 and 3, respectively. In each figure discharges were totalled over 3-day intervals from the start of the drilling operation. The depth of the well at the beginning of each month is shown. Included in the figures with the histograms are cumulative curves of the amounts of material discharged. Approximately 30,800 barrels of bulk mud and 6,400

barrels of SCE discards were discharged into the ocean. Major mineralogy and elements of some typical bulk mud and SCE discharges are presented in Tables 5 and 6 to show basic changes in composition over the life of the well.

Total solids (barite and LGS) and total barite for combined bulk mud and SCE discharges are shown in Figures 4 and 5, respectively. During the entire monitoring program approximately 2,160 metric tons (4.76×10^6 lbs) of solids were discharged. Of that, 752 metric tons (1.66×10^6 lbs) were barite.

Mineralogy and elemental analysis were determined on the major mud additives; barite, bentonite and chrome lignosulfonate. The results are shown in Table 7. The mineralogy of barite and bentonite are typical examples of these additives. The differences in mineralogy between the major additives and the muds discharged (Table 5) reflects the contribution of the hole cuttings. The composition of the cuttings from downhole can be better estimated by considering the mineralogy of the discards from the solid control equipment.

The quantity of different mud components (including drill solids from the hole) added to the mud system during the drilling operation are given in Table 8. The drill solids value was estimated from gauge hole and depth calculations. All the other mud additions were inventoried. Freshwater was used in the mud except for the period February 2-24 when seawater was used.

Also given in Table 8 are the total measured amounts of materials discharged from the mud system (both bulk mud and solids control equipment discharges), plus an estimated amount of material left in the hole upon abandonment. The measured discharges and the estimated material left in the hole closely agree with the measured material added to the mud system.

To assess possible sources of trace metals from drilling discharges, trace metal analyses (Cr, Cd, Pb, Hg, Ni, V and Zn) were conducted on the major mud additives (barite, bentonite, chrome lignosulfonate and lignite) and representative mud and SCE discharges (Tables 9 and 10). Trace metal analyses of the muds used in the dispersion tests are shown in Table 3. The amounts of trace metals added to the mud system by the major additives were estimated from the concentrations in Table 9 and are presented in Table 11. Maximum amounts of trace metals discharged with SCE and mud discharges are given in Table 12. These maximums were estimated from the samples in Table 10. Except for chromium, the reason for the larger amounts of trace metal discharged with SCE and mud discharges (Table 12) compared to those added to the mud system by the major additives (Table 11) is due to additional amounts of trace metals added to the mud system from formation drill solids.

Current roses for the quarters January through March and April through July 11 are presented in Figures 6 and 7, respectively. These figures show the percentages of time that a current of a given speed flows in a given direction. Prominent flow to the south and southwest is evident. The current meter results were vector averaged giving each depth equal weight and combined with the discharge data (quantity and time) to estimate the distribution of discharged material. The results are shown for total solids in Figure 8, barite in Figure 9 and organic chemical material in Figure 10. In each case the vector length is proportional to percentage of the material discharged in the representative current direction. As expected from the current meter data the bulk of material was distributed to the south and southwest of the well site.

Dispersion Tests

Control values for suspended solids, transmittance, pH and salinity ranged from 0.1-2.4 mg/l, 88-89%, 8.0-8.3, and 32.5-33.5 ppt, respectively. None of these variables showed any trend with depth over the depth interval measured (40 meters). Dissolved oxygen and temperature control values ranged from 6.7-11.9 mg/l and 4.9-6.3°C, respectively. Dissolved oxygen values showed a slight maximum around 20 meters, and temperature appeared to decrease slowly with depth.

During both discharge tests two plumes were formed; a lower plume which contained the bulk of the solids and descended rapidly, and an upper plume, which was generated by turbulent mixing of the lower plume with the seawater and remained as a diffuse cloud in the upper portion of the water column. The upper plume was the plume characterized by the helicopter sampling and most of the diver sampling. The 10 meter current speeds were 21.5 cm/sec during the 500 bbl/hr test and 26.9 cm/sec during the 275 bbl/hr test.

Measurements of dissolved oxygen, pH, salinity, and temperature in the discharge plume were unchanged from background values in both tests. Suspended solids concentrations and transmittance were the only water quality parameters that were affected. Table 13 shows suspended solids concentrations and transmittance values versus distance and depth for both tests. These measurements represent the maximum solids and minimum transmittance values detected in the plume at the specified distances.

DISCUSSION

Discharge Monitoring

Over the life of the well, whole mud discharges (bbls) were intermittent in nature (Fig. 2), and generally higher than what would normally be observed in most offshore wells. The reason for the higher discharges was because the "dilution method" was used to control undesirable colloidal solids buildup in the mud. Colloidal solids cause deterioration of the rheological properties of mud. In low-density muds when barite and chemical concentrations are low, discharge of mud and addition of water to the mud system (dilution method) is an economical way to reduce these colloidal solids.

In Fig. 2 the high discharge volumes that occurred around January 15 resulted from replacing the mud system due to excessive solids content. The high discharges around February 24 were due to conversion from seawater mud to freshwater mud. From February 2-24 seawater was used instead of freshwater in the mud system. In the period around April 21 excessive discharges occurred because of the dispersion study. The cumulative curve in Fig. 2 shows that the discharge rate was fairly constant until drilling stopped around May 25.

In contrast to the whole mud discharges, the SCE discharges (bbls) (Fig. 3) were large at the beginning of the well and gradually tapered off to a small amount by April. This is typical of most wells and reflects the decreasing hole size and decreasing drilling rate that occurs as drilling proceeds. The intervals of no discharge that occurred after January 16, January 31, March 23, April 22, and May 29 were due to drilling interruptions in order to set casing and log the well.

Total solids (LGS plus barite) discharged from the mud pits and solids control equipment were fairly typical of wells drilled to this depth (Fig. 4). Most of the discharges in the first few months were attributed to SCE discards (Fig. 3) which were primarily composed of low gravity solids from the borehole (Table 7). Solids discharges in the later months were mostly due to whole mud discharges and contained higher concentrations of barite (Fig. 5).

Forty percent (863 metric tons) of the total solids discharged were from the solids control equipment. Of this 863 tons, 41% was processed by the shale shakers, 40% by the desander, and 19% by the mud cleaners. Seventy-seven percent of the SCE discharges occurred in January and February (56% in January alone). During January and February, 66% of the total shale shaker discards, 96% of the desander discards, and 55% of the mud cleaner discards were discharged. Of all the solids discharges from the solid control equipment, only 50 metric tons was barite (6.5% of all the barite discharged).

Mineralogy and elemental analysis results in Table 7 (for one desander and two shale shakers) represent typical SCE samples taken during the period of highest volume discharges. Since SCE discards reflect the cuttings content of the borehole, samples in the table also represent two (out of three) major downhole lithological sections drilled. The January and February samples depict the clay-sand section of the upper part of the hole while the March sample represents a more varied mineralogical section of the middle part of the hole.

Solids from whole mud discharges amounted to 1,287 metric tons of which 700 metric tons (54%) was barite (the rest LGS). Ninety three percent of the barite was associated with bulk mud discharges. Approximately 50% of the barite discharged in the whole mud discharges (SCE is negligible) occurred in the month of May alone (Fig. 5). Mineralogy and elemental analysis results for some representative whole mud discharges given in Table 5 show the gradual increases in barite content with time (and well depth). These barite increases, however, do not correspond to major increases in mud weight. This is a result of maintaining optimum performance of the mud by decreasing the total solids content. Only at the beginning of May did mud weight, solids and barite content begin to climb (approximately 12 lbs/gal, 40% of mud and 75% of solids, respectively). As mentioned before, seawater was used in the mud instead of freshwater from February 2-24. This is reflected in the Table by the high calcite and halite concentrations in the February sample. The high montmorillonite contents in the mud samples partially reflect the continuous addition of bentonite to the mud system.

The material balance on all the major additives and components in the mud and SCE discharges (Table 8) shows that the amount of added solids, barite and bentonite (1,280 metric tons) was only slightly greater than the amount of drill solids from the hole (1,168 metric tons). Close to 83% of the bentonite used is montmorillonite with small percentages of other minerals while 90% of barite used consists of barium sulfate with the major impurity being quartz (Table 7).

Equal amounts of chrome lignosulfonate and lignite were added to the mud system throughout the drilling operation (Table 8). Very rarely was one added without the other. Seventeen percent of the chrome lignosulfonate was ash of which 16% was chromium (Table 7). Chromium makes up 2.91% by weight of dried chrome lignosulfonate. Approximately 90% of the organic chemicals was associated with mud discharges.

Fifty metric tons of caustic were added to maintain the pH near 11. The only other additives used in the mud system were the minor ones shown at the bottom of Table 8. The amount of material discharged plus that left in the hole agrees well with the quantity of material added (5-7% unaccounted for material).

Trace metal analyses of major mud additives, mud discharges, and solid control equipment discards (Tables 3, 9, and 10) were conducted to determine if drilling discharges could account for possible changes of trace metal concentrations in the sediment and benthic community. Samples in Table 9 and 10 were analyzed by a different laboratory using different detection limits than those in Table 3. Trace metal concentrations in the major additives (Table 9) were all below detectable limits except for zinc in bentonite and organic chemicals, and chromium in chrome lignosulfonate. Chrome lignosulfonate was the major source of chromium in all the discharges.

In the representative mud and SCE discharges (Table 10), and the dispersion test samples (Table 3), cadmium concentrations were below 2 mg/kg of dry solids. Mercury was less than 3 mg/kg in all the representative samples (Table 10) and below 0.05 mg/kg in the dispersion test muds (Table 3). Nickel and vanadium were 35 mg/kg or less in all the discharges while zinc concentrations ranged from 100-250 mg/kg. Zinc was approximately 40 mg/kg in the acid leached samples from the dispersion test muds. In one SCE sample and the dispersion test muds lead values ranged from 103-241 mg/kg. The other five representative mud and SCE samples had lead values of 16 mg/kg or less.

From Table 11 and 12 it appears that the source of the cadmium, mercury, nickel and vanadium in the discharges lies in the drill solids. The amounts of nickel and vanadium in the mud additives were considerably lower than those discharged. The small quantities of cadmium and mercury discharged could be partially derived from the additives; however, the lower limit of detection prevents closer investigation.

Approximately 480 kg of zinc (Table 12) was discharged, most of it attributed to drill solids; however, bentonite (Zn~25 kg) and drill collar and pipe dope (Zn~57 kg) could be contributors also. Lead discharges were estimated to be 33 kg. Most of this metal could be associated with drill dope (48 kg). It should be emphasized that the estimates of metals (Cu, Pb, Zn) added from drill collar and pipe dope are maximum possible values since the amount of dope actually entrained in the mud system is not known. Sporadically high concentrations of metals in the mud may be justifiably associated with drill dope contamination. The amount of chromium added to the mud system (1,315 kg = 94% of 1,400 kg) agrees well with the estimated value of chromium discharged (1,378 kg).

The distribution of discharged material in the marine environment is assumed to follow the weighted-average current direction at the time of discharge. In Figures 8, 9, and 10 approximately 60-70% of the total solids, barite, and organic chemical were carried away from the rig in a south-southwesterly direction. The total solids and organic chemical were generally carried to the southwest while barite was carried more directly to the south. Prevailing currents were more to the south during the latter stages of the well when barite discharges were highest accounting for the slight shift in direction of the barite distribution. The organic chemical distribution also reflects the distribution of discharged chromium (from chrome lignosulfonate). Over the life of the well, 1.4 metric tons of chromium were discharged. The distributions shown in the Figures were used by

Mariani et al. (1980) and Menzie et al. (1980) to correlate changes in the sediment and benthic community with drilling discharges.

Dispersion Study

The behavior of the discharged mud was similar to that observed in earlier tests using a high density mud as reported by Ayers et al. (1980). The lower plume which contained the bulk of the solids descended rapidly and the upper plume, generated by turbulent mixing of the lower plume with seawater, remained as a diffuse cloud in the upper portion of the water column and drifted away from the source with the current.

The only water quality variables that were affected by the discharge were suspended solids and transmittance. This is in agreement with earlier work (Ecomar 1978; Ayers et al. 1980). During the 500 bbl/hr test two high suspended solids concentration samples were taken by the divers (Table 13); one just inside the bottom of the discharge pipe (100,400 mg/l) and one 15 meters downcurrent and at a depth of 24 meters (1,195 mg/l). These samples were undoubtedly obtained from the lower plume and trace the path of the lower plume near the source. All the other samples were taken in the upper plume. During the 275 bbl/hr test only one sample (1,398 mg/l) was taken in the lower plume and that was just inside the bottom of the discharge pipe. Suspended solids levels of samples taken inside the bottom of the pipe were 2-100 times less concentrated than the discharged mud, indicating some dilution occurred in the pipe due to intrusion of ambient seawater.

Suspended solids concentrations near the source were higher in the 500 bbl/hr test. In both tests the concentration of solids dropped off quickly with distance. Background suspended solids levels were reached around 350 meters during the 500 bbl/hr test and 600 meters during the 275 bbl/hr test. Within 150 meters of the discharge source during the 500 bbl/hr test, the plume flattened noticeably near the surface and was not detectible below five meters. During the 275 bbl/hr test the plume center remained ten to fifteen meters deep out to a distance of about 600 meters. The near surface current velocity was much less than the current at ten meters during both tests and accounts for the suspended solids concentration reaching background closer to the source during the 500 bbl/hr test. Transmittance values did not reach background as quickly as suspended solids levels. During the 275 bbl/hr test transmittance values reached background (i.e., the plume was no longer visible) 800-1,000 meters downcurrent of the source. Suspended solids reached background at 600 meters. It was not possible to measure the point when transmittance reached background during the 500 bbl/hr test due to the onset of darkness. During a 1,000 bbl/hr discharge test in the Gulf of Mexico Ayers et al. (1980) background transmittance values were reached 1,500 meters downcurrent of the discharge sources (suspended solids concentrations reached background around 1,000 meters). The reason it takes longer for transmittance values to reach background is because fine colloidal particles are present in concentrations sufficiently high to scatter light but too low to contribute significantly to suspended solids values. This is discussed in Ayers et al. (1980).

CONCLUSIONS

- o During the six months drilling phase of the program, 752 metric tons of barite, 1,409 metric tons of low gravity solids (bentonite plus natural formation drill solids) and 94 metric tons of organic chemical (chrome lignosulfonate, lignite, and cellulose polymer) were discharged. Of the

2,161 tons of solids which were discharged, 60% were associated with mud discharges and 40% with solids control equipment discharges. Approximately 93% of the barite was associated with mud discharges.

- o The majority of the discharged material was carried away from the rig in a south-southwesterly direction by the prevailing currents. The low gravity solids were distributed more to the southwest, and the barite and organic chemical more to the south.
- o Natural formation drill solids were a major source of most trace metals in the discharges. Some of the additives (bentonite and pipe dope) may have contributed to lead and zinc values in the discharged material.
- o The behavior of discharged mud during the dispersion test was similar to that observed in earlier tests. The discharge formed two plumes, a lower plume which contained the bulk of the solids, and descended rapidly, and an upper plume generated by turbulent mixing of the lower plume with seawater which remained as a diffuse cloud in the upper portion of the water column and drifted away from the source with the current.
- o The only water quality parameters affected by the upper plume were suspended solids concentration and transmittance. Suspended solids concentrations reached background at 350-600 meters downcurrent of the discharge source. Transmittance values reached background 800-1,000 meters downcurrent. Because of the rapid decrease in suspended solids concentrations with distance and the temporary and minor effect on seawater hydrography (transmittance only), it appears that the drilling discharges had a negligible effect on the near-surface water quality of the area.

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Table 1

Scheme for Determining Organic Chemical,
Salt and Solids Content in Mud Sample

Given:

LGS Density	= 2.6 g/cm ³
Barite Density	= 4.5 g/cm ³
Salt Density	= 1.81 gm/cm ³
Organic Chemical Density	= 1.0 g/cm ³
Water Density	= 1.0 g/cm ³
Organic Chemical Weight Loss Fraction at 600°C (z)	= 0.83
Inorganic Material (LGS) Weight Loss Fraction at 600°C (FCL)	= 0.05

Measured Quantities:

Mud Density (lbs/gal or g/cm ³)	= ((Pycnometer & Sample Weight) - Pycnometer Weight)/((Pycnometer volume) + (Pycnometer & Sample Weight) - (Pycnometer & Sample & Water Weight))
Chlorides (mg/l)	
Sample Weight	= Total Weight - Container Weight
Dried Weight	= Dried (100°C) Sample Weight - Container Weight
Water Weight	= Sample Weight - Dried Weight
Fired Weight	= Fired (600°C) Sample Weight - Dried (100°C) Sample Weight

Calculations:

First Estimate of Specific Gravity of Solids

Solids Volume	= (Sample Weight/Mud Density) - (Water Weight/Water Density)
Solids Weight	= Dried (100°C) Weight
Solids Density	= Solids Weight/Solids Volume

Table 1 (Continued)

Start of Iteration

Volume Fraction of LGS in Solids	=	(Density of Solids - Density of Barite)/ (Density of LGS - Density of Barite)
Weight Fraction of LGS in Solids	=	(Density of LGS x Volume Fraction of LGS)/Density of Solids
Weight Fraction of Barite in Solids	=	1.- Weight Fraction of LGS in Solids
Weight of Combustible Inorganic Material	=	(Weight Frac of LGS in Solids) x (Solids Weight) x FCL
Weight of Combustible Organic Chemical	=	Fired Weight - Weight of Combustible Inorganic Material
Weight of Salt	=	$K_1 \times (\text{Chlorides} \times \text{Water Weight} \times$ $10^{-6}/\text{Water Density})$
K_1	=	1.65×3.5 $\text{Cl}^- < 1500 \text{ mg/l}$ $1.65 \times [1.0 + 2.5 (1.0 - \frac{\text{Chlorides (mg/l)}}{15,000})]$ $1500 < \text{Cl}^- < 15,000$ 1.81×1.0 $\text{Cl}^- > 15,000$
Solids Volume	=	(Sample Weight/Mud Density) - (Water Weight/Water Density) - (Salt Weight/Salt Density) - (Organic Chemical Weight/Org Chem Density)
Solids Weight	=	Dried Weight - Salt Weight - Organic Chemical Weight
Solids Density	=	Solids Weight/Solids Volume
Return to Start of Iteration		

Continue Until Solids Density Difference Between Last and Previous
Iteration is 0.001.

Table 2

Analytical Techniques and Corresponding Relative
Percent Error For Mineralogical and Elemental Determinations

	<u>Analysis Technique *</u>	<u>Relative Error</u>
Barium	X-D	±10%
	X-F	±10%
	NA	± 6%
Minerals	X-D	±15%
Major Elements (Semi-Quantitative)	X-D	±10-20%
Aluminum	NA	± 3%
Chromium	NA	± 3%
	AA	± 3%
Cadmium	AA	± 5%
Lead	AA	± 5%
Mercury	AA	±10%
Nickel	AA	± 3%
Vanadium	AA	±10%
Zinc	AA	± 5%

*X-D X-ray Diffraction - Spectrographic Analysis
 X-F X-ray Fluorescence Analysis
 NA Neutron Activation Analysis
 AA Atomic Absorption Analysis

Table 3

Composition, Properties and Elemental Analysis
of Mud Discharged During Dispersion Tests

<u>Component</u>	<u>Composition (wt. %) and Properties</u>	
	<u>500 BBL/HR</u>	<u>275 BBL/HR</u>
Barite	15.0	15.9
LGS	6.5	7.5
Chrome lignosulfonate	1.0	1.0
Lignite	1.0	1.0
Inorganic Salts	0.7	0.7
Water	75.8	73.9
Density (g/cc)	1.19	1.21
pH	11.4	10.9
Solids (mg/l)	250,400	277,400
<u>Element</u>	<u>Metals Analysis, mg/kg*</u>	
	<u>500 BBL/HR</u>	<u>275 BBL/HR</u>
Ba	229,100	303,700
Cr	1112	1159
As	1.8	2.3
Cd	0.6	0.8
Cu	7.7	5.8
Hg	<0.05	<0.05
Ni	13.5	17.0
Pb	102.6	218.5
V	22.7	28.0
Zn	48.4	36.0

*All metal analyses are on dry weight basis; Ba and Cr were analyzed by Neutron Activation Analysis; the other metals were analyzed after acid leaching by Atomic Absorption at the University of Delaware.

Table 4

Gauge Hole and Casing Size at
Specified Depths From Seafloor

<u>Gauge Hole</u>		<u>Casing</u>	
<u>Hole Size</u>	<u>Depth</u>	<u>Casing Size</u>	<u>Depth</u>
(dia-cm)	(m)	(dia-cm)	(m)
91.4	82.3	76.2	82.3
66.0	281.9	50.8	262.4
44.5	1200.9	34.0	1188.7
31.1	3741.2	24.4	3727.8
21.6	4969.5	17.8	4667.8

Table 5

Representative Mud Discharge Mineralogy
and Elemental Analyses Results

X-ray Diffraction Analysis (Dried Weight Percent)

	<u>Feb. 22, 10 AM</u>	<u>Mar. 25, 10 PM</u>	<u>April 27, 8 PM</u>
	<u>%</u>	<u>%</u>	<u>%</u>
<u>Mineral</u>			
Barite	5.1	30.6	58.7
Montmorillonite	38.0	34.0	23.7
Illite	10.6	7.8	5.0
Illite/Montmorillonite	5.8	4.6	3.0
Kaolinite	4.6	3.8	1.3
Chlorite	3.5	1.9	-
Muscovite	6.7	5.0	2.3
Quartz	10.8	6.0	5.1
Feldspar	0.5	1.0	0.3
Calcite	6.8	3.3	0.4
Cristobalite	0.9	0.3	0.2
Halite	6.7	1.7	-
% Solids (Wt%)	23.5	21.0	26.0
Mud Density (g/cc)	1.16	1.16	1.22
Bbls Discharged	250	770	315

Spectrographic Analysis (Dried Weight Percent)

	<u>Feb. 22, 10 AM</u>	<u>Mar. 25, 10 PM</u>	<u>April 27, 8 PM</u>
	<u>%</u>	<u>%</u>	<u>%</u>
<u>Element</u>			
Aluminum	10.0	10.0	6.0
Barium	3.0	18.0	35.0
Calcium	4.0	3.0	0.6
Chloride	4.0	1.0	0.3
Chromium	0.06	0.04	0.02
Copper	0.02	0.01	0.01
Iron	2.0	1.0	0.8
Magnesium	1.0	0.7	0.4
Manganese	0.04	0.03	0.01
Potassium	0.8	0.8	0.3
Rubidium	0.01	0.005	-
Silicon	24.0	18.0	11.0
Sodium	5.0	2.0	2.0
Strontium	0.2	0.1	0.1
Sulfur	2.0	5.0	8.0
Titanium	0.6	0.4	0.3
Zinc	0.04	0.03	0.01

Table 6

Representative Solids Control Equipment Discard
Mineralogy and Elemental Analyses Results

<u>Mineral</u>	<u>X-Ray Diffraction Analysis (Dried Weight Percent)</u>		
	<u>Jan. 13, 8 AM</u>	<u>Feb. 17, 4 PM</u>	<u>Mar. 16, 4 PM</u>
	<u>Desander</u>	<u>Shale Shaker</u>	<u>Shale Shaker</u>
	%	%	%
Barium Sulfate	6.0	<1.0	2.8
Montmorillonite	5.1	2.1	21.4
Illite	9.2	2.1	11.2
Illite/Montmorillonite	3.2	-	-
Kaolinite	1.1	2.6	11.2
Chlorite	1.1	1.3	5.7
Muscovite	2.1	-	4.6
Quartz	44.6	76.0	22.5
Feldspar	19.2	7.8	8.2
Cristobalite	0.2	-	0.2
Calcite	1.5	0.5	5.0
Dolomite	2.0	-	-
Halite	1.2	1.0	-
Pyrite	-	0.3	1.8
Siderite	-	6.0	4.0
Riebeckite	5.3	-	-
% Solids (Wt %)	60.85	77.12	65.42
Sample Density (g/cc)	1.59	1.89	1.68

<u>Element</u>	<u>Spectrographic Analysis (Dried Weight Percent)</u>		
	<u>Jan. 13, 8 AM</u>	<u>Feb. 17, 4 PM</u>	<u>Mar. 16, 4 PM</u>
	<u>Desander</u>	<u>Shale Shaker</u>	<u>Shale Shaker</u>
	%	%	%
Aluminum	7.0	7.0	11.0
Barium	4.0	0.4	1.6
Calcium	1.0	0.9	3.0
Chloride	0.7	0.5	0.1
Copper	0.01	-	-
Iron	2.0	3.0	4.0
Magnesium	1.0	0.2	0.2
Manganese	0.1	0.04	0.04
Potassium	1.0	0.8	1.0
Rubidium	0.02	0.02	0.01
Silicon	32.0	37.0	26.0
Sodium	2.0	0.8	0.8
Strontium	0.1	0.03	0.04
Sulfur	0.8	0.8	2.0
Titanium	0.4	0.4	0.3
Zinc	0.05	0.01	0.09

Table 7

Major Additive Mineralogy and
Elemental Analysis Results

X-ray Diffraction Analysis (Dried Weight Percent)

<u>Mineral</u>	<u>Barite</u> %	<u>Bentonite</u> %	<u>Chrome lignosulfonate</u> <u>(Ash)*</u> %
Barium Sulfate	90.0		
Montmorillonite		82.5	
Biotite Mica		3.1	
Cristobalite		3.7	
Quartz	6.0	3.6	
Calcite		1.4	
Feldspar		5.1	
Gypsum		0.6	
Amorphous (SiO ₂)	4.0		
Cr ₂ O ₃			23
Sulfates (Na, Ca, Mg, K)			77

Spectrographic Analysis (Dried Weight Percent)

<u>Element</u>	<u>Barite</u> %	<u>Bentonite</u> %	<u>Chrome lignosulfonate</u> <u>(Ash)</u> %
Aluminum		12.0	
Barium	55.0	0.007	
Calcium	0.03	1.0	7.0
Chromium			16.0
Copper	0.01		
Iron	0.1	2.0	0.2
Magnesium	0.1	0.8	0.6
Manganese		0.1	
Potassium	0.01	0.5	1.0
Silicon	3.0	32.0	0.1
Sodium	0.1	1.0	17.0
Strontium	0.1	0.2	0.3
Sulfur	13.0	0.1	17.0
Titanium		0.1	0.05
Zinc		0.01	0.01

*Ash at 600°C was 17% of dry weight.

Table 8
Total Mud System Material Balance
(Metric Tons)

<u>Mud Components</u>	<u>Added*</u>	<u>Discharged</u>	<u>Left in Hole</u>	<u>% Added Unaccounted for</u>	
Barite	866	752	52	7%	
Bentonite	413	1581	1409	20	9%
Drill Solids	1168				
Lignite	47	99	94	-	5%
Chrome Lignosulfonate	48				
Drispac	4.3				

*Other additives: Caustic (NaOH) - 50.2 metric tons, SAPP (Sodium acid pyrophosphate) - 635 kg, Lime (Ca(OH)₂) - 408 kg, Magconol (defoamer) - 360 liters, Cottonseed Oil - 76 liters, Aluminum Stearate - 4.5 kg, Drill Pipe Dope (15% Cu, 7% Pb) - 250 kg, Drill Collar Dope (35% Zn, 20% Pb, 7% Cu) - 160 kg.

Table 9

Metals Analysis of Major
Additives (Dry Weight Basis)

<u>Metal*</u>	<u>Barite</u>	<u>Bentonite</u>	<u>Chrome Lignosulfonate/ Lignite (1:1)</u>
Chromium	<10	<10	14,600
Cadmium	< 2	< 2	< 2
Lead	<10	<10	<10
Mercury	< 1	< 1	< 1
Nickel	< 5	< 5	< 5
Vanadium	<10	<10	<10
Zinc	< 5	57	15

*(AA) Atomic Absorption Analysis after total digestion - SCR, Inc.

Units in mg/kg.

Lower limits for metals analyzed by atomic absorption analysis are:

Cr - 10 mg/kg, Cd - 2 mg/kg, Pb - 10 mg/kg, Hg - 1 mg/kg, Ni - mg/kg,
V - 10 mg/kg, Zn - 5 mg/kg.

Table 10

Metals Analysis of Some Typical Mud
Discharges and SCE Discards (Dry Weight Basis)

<u>Metal*</u>	<u>Mud Discharges</u>		
	<u>Concentration, mg/kg</u>		
	<u>Feb. 22, 10 AM</u>	<u>Mar. 25, 10 PM</u>	<u>April 27, 8 PM</u>
Barium (NA)	24,000	178,000	306,000
Aluminum (NA)	64,000	54,000	38,000
Chromium (AA)	790	910	1,007
Cadmium (AA)	<2	<2	<2
Lead (AA)	14	16	<10
Mercury (AA)	<1	1.9	2.2
Nickel	15	21	10
Vanadium (AA)	32	25	<10
Zinc (AA)	236	236	141
% Dry Solids in Mud	23.54	20.94	26.02
Mud Density (g/cc)	1.16	1.16	1.22

SCE Discards

<u>Metal*</u>	<u>Concentration, mg/kg</u>		
	<u>Jan. 13</u>	<u>Jan. 28</u>	<u>Feb. 17</u>
	<u>Desander</u>	<u>Shale Shaker</u>	<u>Shale Shaker</u>
Ba (X-FL)	19,300	823	4100
Chromium (AA)	57	90	57
Cadmium (AA)	<2	<2	<2
Lead (AA)	241	<10	14
Mercury (AA)	2.8	1.8	<1
Nickel (AA)	24	33	20
Vanadium (AA)	16	20	14
Zinc (AA)	197	101	104
% Dry Solids in Sample	60.85	67.3	77.12
Sample Density (g/cc)	1.59	1.70	1.89

*(AA) Atomic Absorption Analysis after total digestion - SCR, Inc.

(NA) Neutron Activation Analysis - Uranium West Labs.

(X-FL) X-ray Fluorescence - SCR, Inc.

Lower limits for metals analyzed by atomic absorption analysis are:

Cr - 10 mg/kg, Cd - 2 mg/kg, Pb - 10 mg/kg, Hg - 1 mg/kg, Ni - 5 mg/kg,
V - 10 mg/kg, Zn - 5 mg/kg.

Table 11

Estimated Quantities of Trace Metals
Entering Mud System from Major Additives*

<u>Metal</u>	<u>Barite, kg</u>	<u>Bentonite, kg</u>	<u>Chrome Lignosulfonate and Lignite, kg</u>	<u>Total, kg</u>
Cr	< 9	< 4	1400	1400
Cd	< 2	< 1	< 0.2	< 3
Pb	< 9	< 4	< 1	< 14
Hg	< 1	< 0.4	< 0.1	< 2
Ni	< 4	< 2	< 0.5	< 7
V	< 9	< 4	< 1	< 14
Zn	< 4	24	2	< 30

*If all drill and pipe collar dope entered mud system the following quantities would be added: Pb - 48 kg, Zn - 57 kg.

Table 12

Estimated Maximum Quantity of
Trace Metals Discharged*

<u>Metal</u>	<u>Solids Control Equipment Discards, kg</u>	<u>Mud Discharges, kg</u>	<u>Total, kg</u>
Cr	78	1300	1378
Cd	< 2	< 3	< 5
Pb**	12	21	33
Hg	2	3	5
Ni	29	27	56
V	17	41	58
Zn	170	304	474

*Estimates based on maximum concentrations shown in Table 10.

**Does not include atypically high value of 241 mg/kg in Table 10.

Table 13

Suspended Solids Concentration and Transmittance
vs Distance During Dispersion Tests

500 Barrel/Hour - 500 Barrels Discharged

<u>Distance From Source, m</u>	<u>Depth, m</u>	<u>Solids Concentration, mg/l</u>	<u>Transmittance, %</u>
Whole Mud Concentration	-	250,400	-
0	14	100,400	-
5	12	82	-
15	11	26	-
15	24	1195	-
119	10	5.1	72
149	1	4.9	61
193	3	4.6	90
332	1	1.8	88
352	1	1.0	86
Background	2-40	0.1-2.4	88-94

275 Barrel/Hour - 220 Barrels Discharged

<u>Distance From Source, m</u>	<u>Depth, m</u>	<u>Solids Concentration, mg/l</u>	<u>Transmittance, %</u>
Whole Mud Concentration	-	277,400	-
0	12	1,398	-
5	12	56	-
15	14	122	-
73	14	12.5	67
89	14	9.7	63
93	10	5.2	73
97	23	4.2	76
192	16	3.5	82
590	7	0.4	94
701	7	1.3	95
Background	2-39	0.1-1.6	96-99

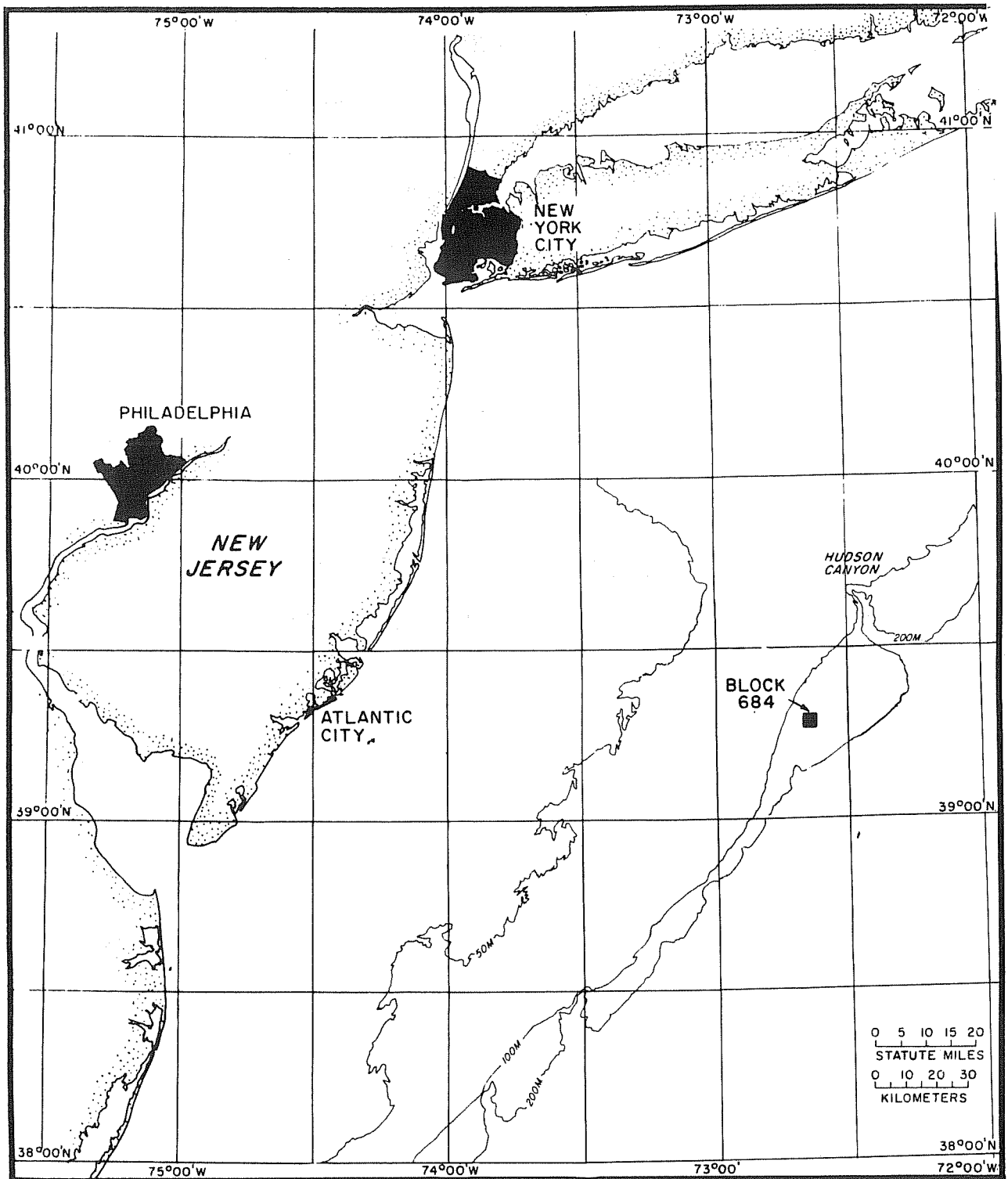


Figure 1

Study Site

MID-ATLANTIC MONITORING PROGRAM HISTOGRAM AND CUMULATIVE CURVE OF WHOLE MUD DISCHARGES

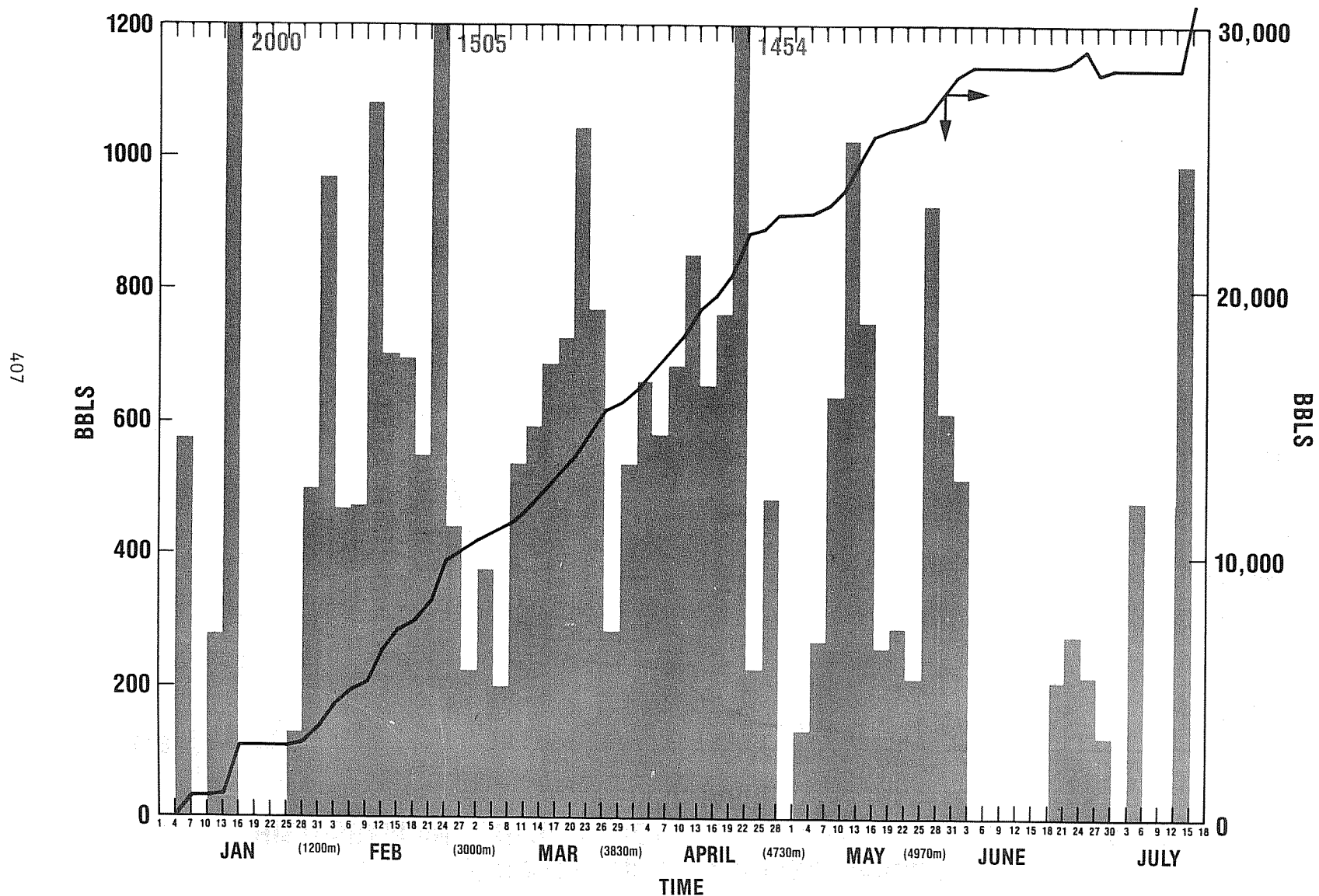


Figure 2

MID-ATLANTIC MONITORING PROGRAM HISTOGRAM AND CUMULATIVE CURVE OF SOLIDS CONTROL EQUIPMENT DISCHARGES

408

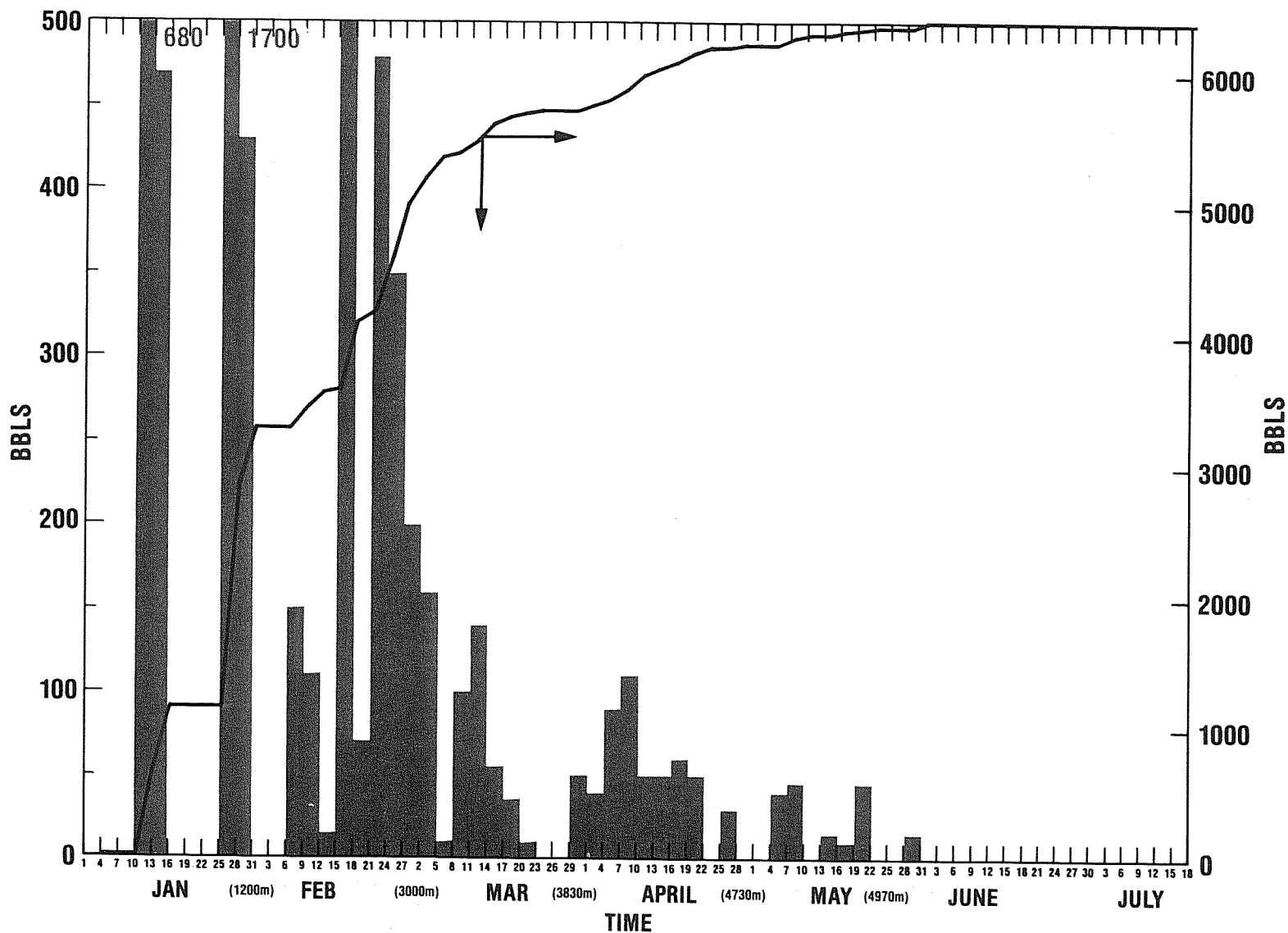


Figure 3

MID-ATLANTIC MONITORING PROGRAM HISTOGRAM AND CUMULATIVE CURVE OF TOTAL SOLIDS (MD & SCE) DISCHARGES

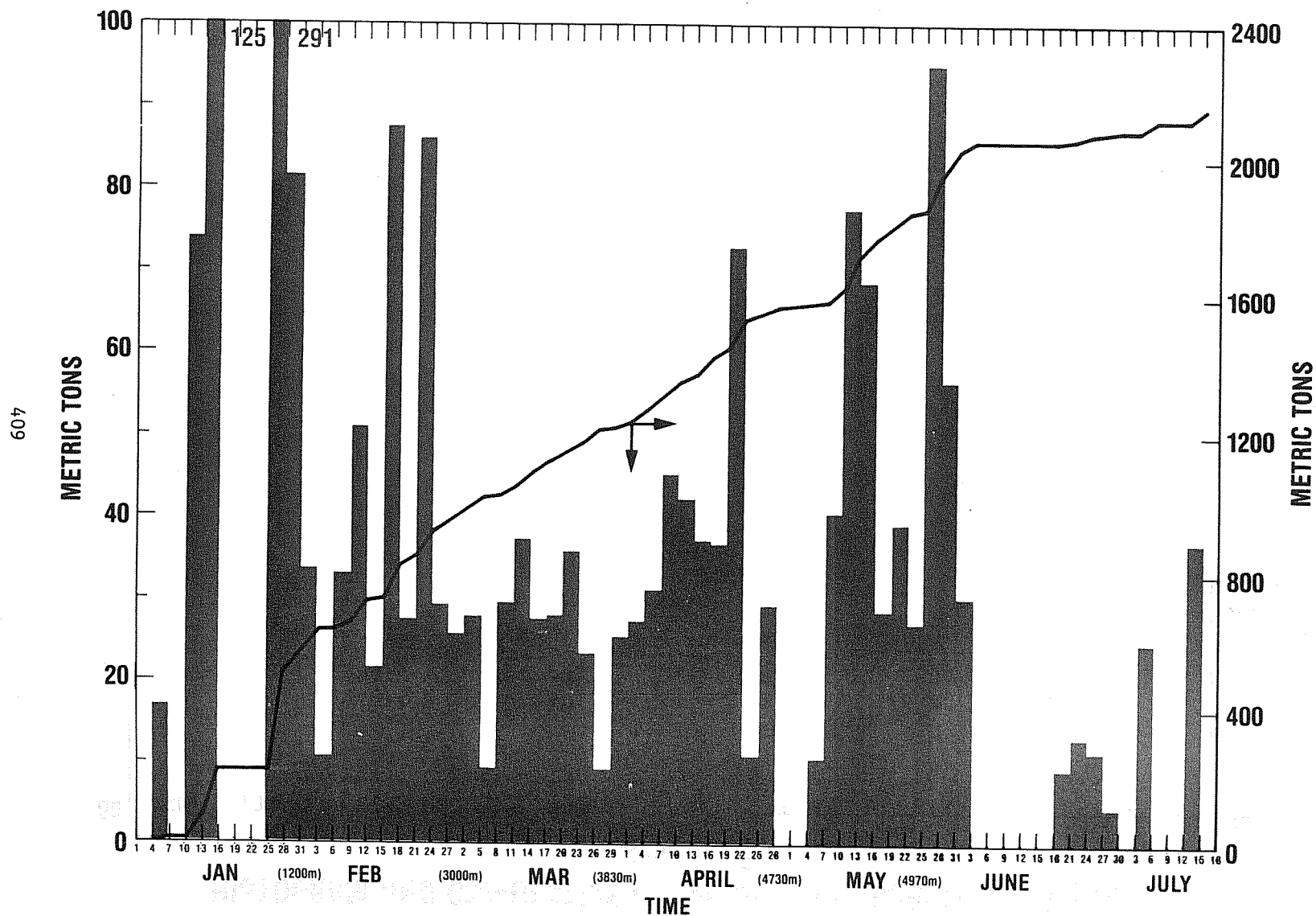


Figure 4

MID-ATLANTIC MONITORING PROGRAM HISTOGRAM AND CUMULATIVE CURVE OF TOTAL BARITE (MD & SCE) DISCHARGES

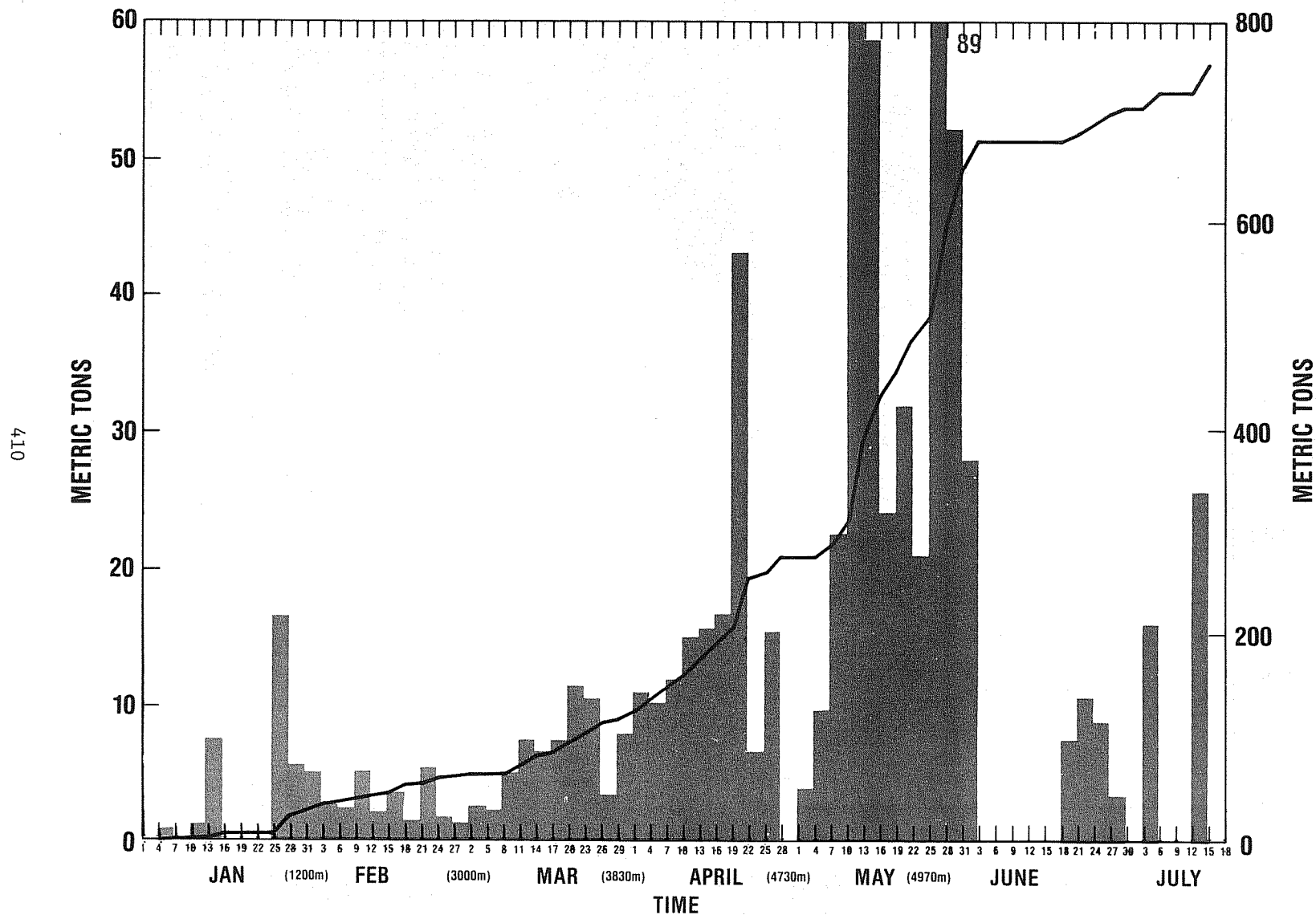


Figure 5

CURRENT ROSES FOR JANUARY - MARCH, 1979

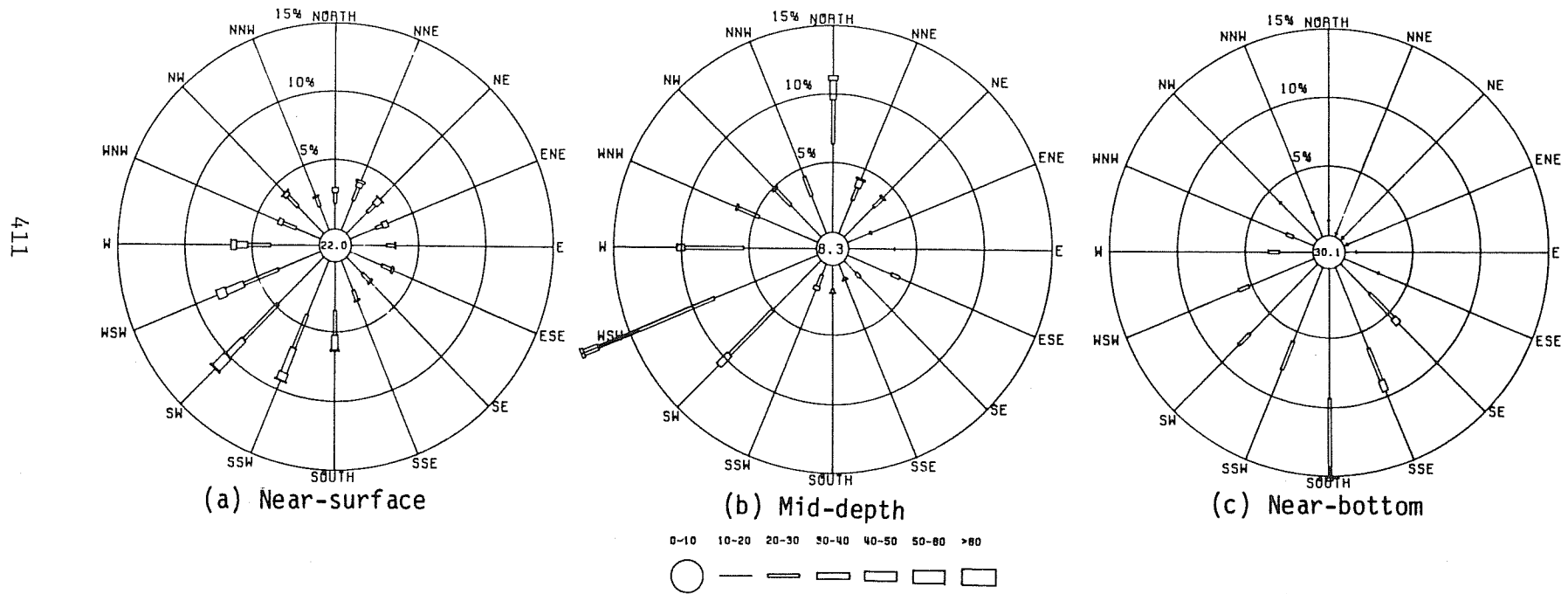
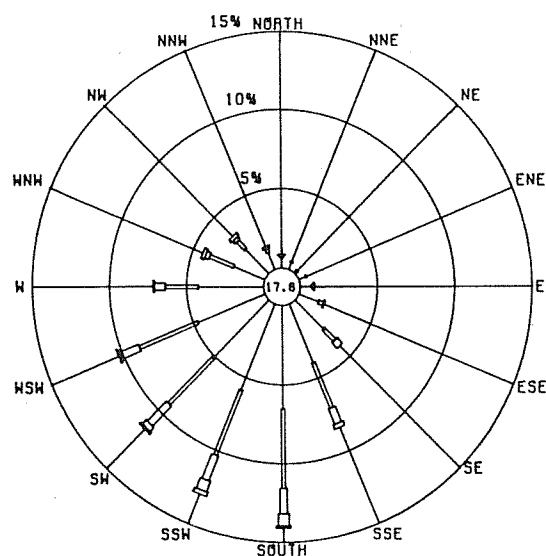
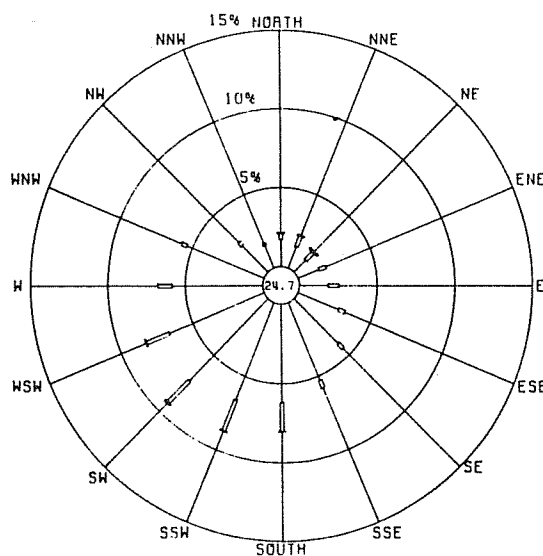


Figure 6

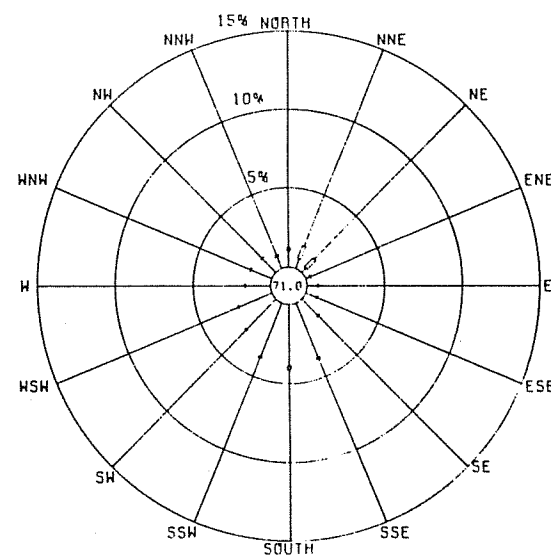
CURRENT ROSES FOR APRIL - JULY, 1979



(a) Near-surface



(b) Mid-depth



(c) Near-bottom

0-10 10-20 20-30 30-40 40-50 50-60 >60

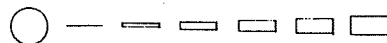


Figure 7

MID-ATLANTIC MONITORING PROGRAM DISTRIBUTION OF TOTAL SOLIDS DISCHARGED*

*-VECTOR LENGTH IS PROPORTIONAL TO PERCENTAGE OF SOLIDS DISCHARGED
IN REPRESENTATIVE CURRENT DIRECTION.

TOTAL SOLIDS DISCHARGED = 2161 METRIC TONS

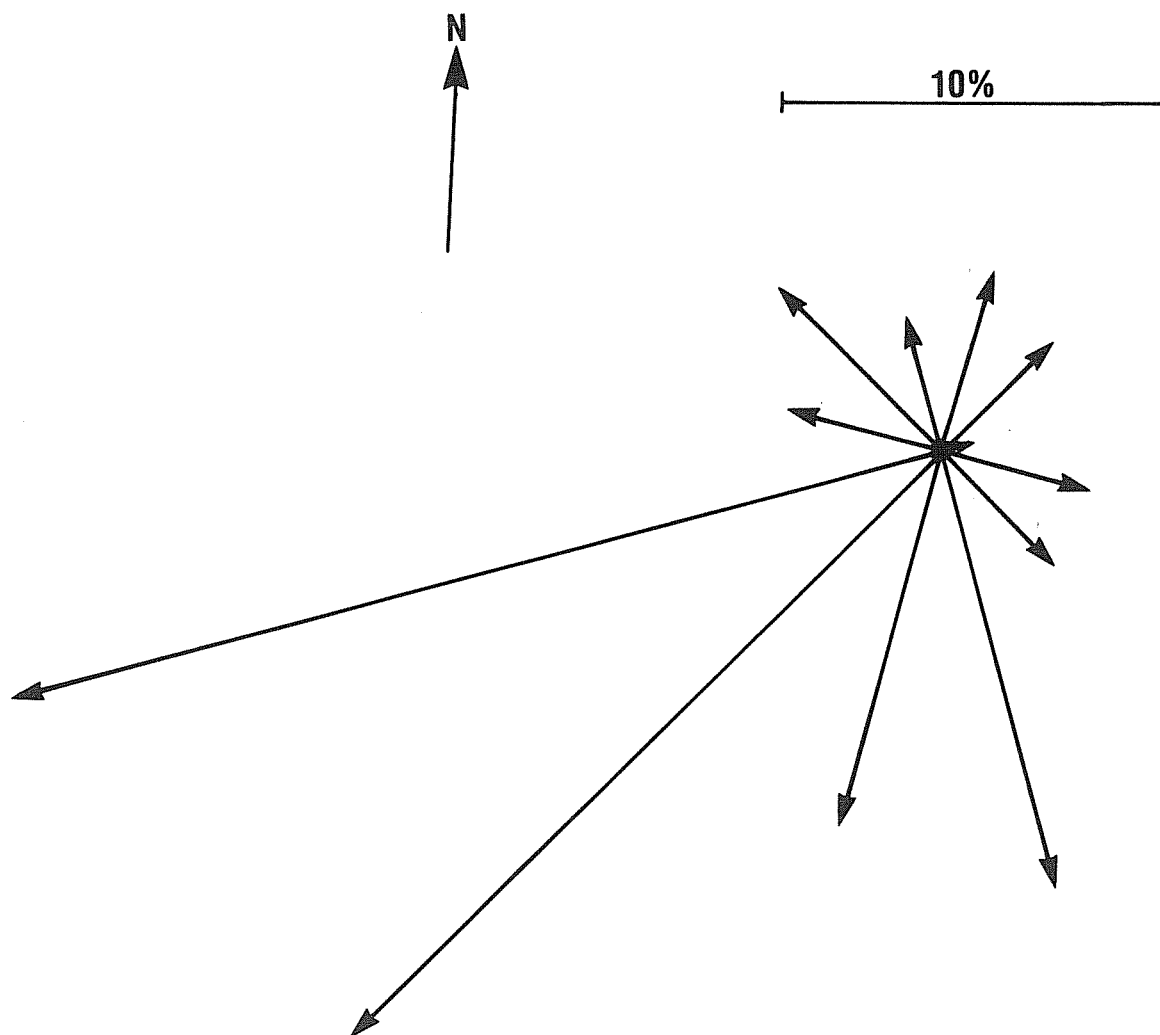


Figure 8

MID-ATLANTIC MONITORING PROGRAM DISTRIBUTION OF TOTAL BARITE DISCHARGED*

*-VECTOR LENGTH IS PROPORTIONAL TO PERCENTAGE OF BARITE DISCHARGED
IN REPRESENTATIVE CURRENT DIRECTION.

TOTAL BARITE DISCHARGED = 752 METRIC TONS

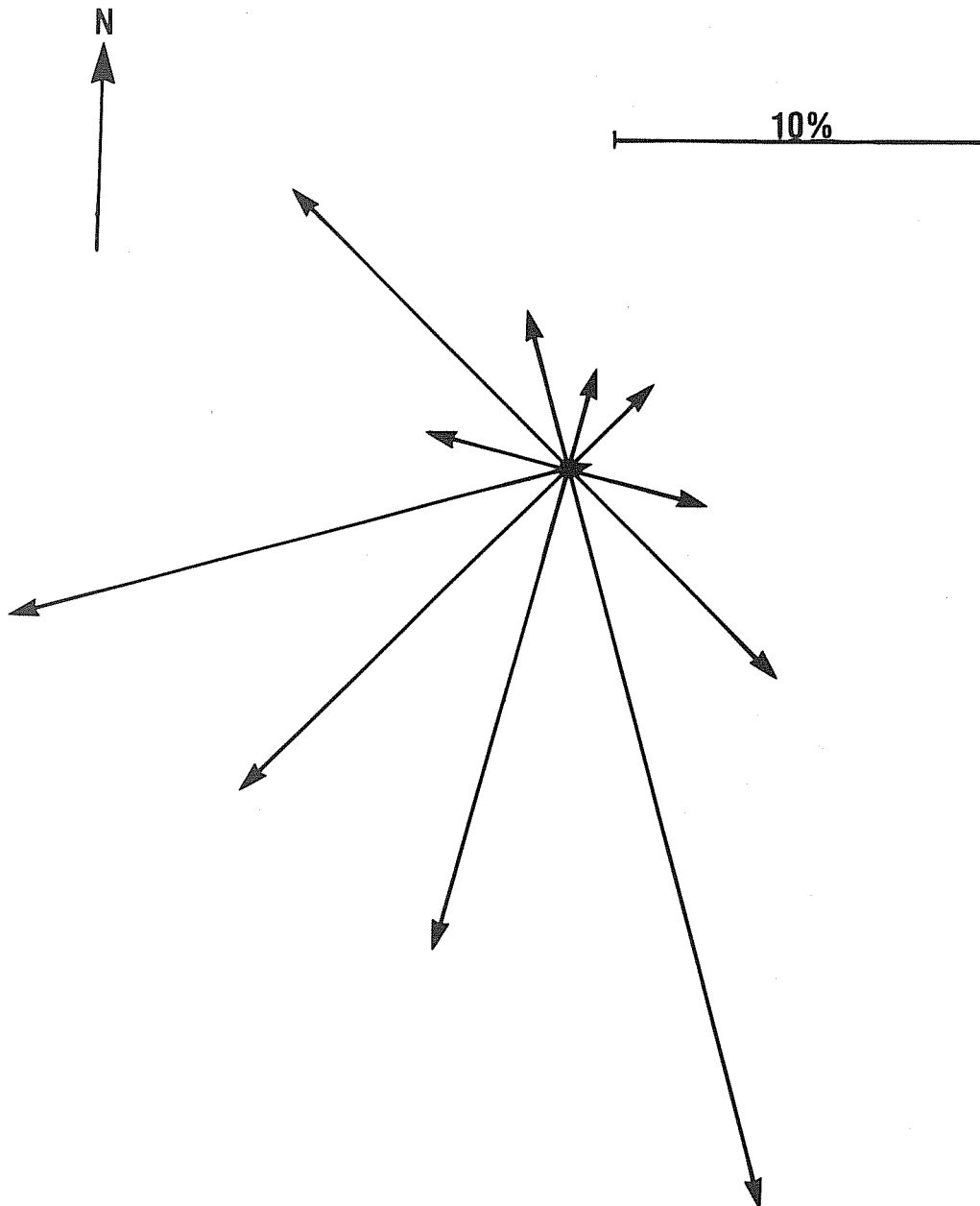


Figure 9

MID-ATLANTIC MONITORING PROGRAM DISTRIBUTION OF TOTAL ORGANIC CHEMICAL DISCHARGED*

*-VECTOR LENGTH IS PROPORTIONAL TO PERCENTAGE OF ORGANIC CHEMICAL DISCHARGED IN REPRESENTATIVE CURRENT DIRECTION.

TOTAL ORGANIC CHEMICAL DISCHARGED = 94 METRIC TONS

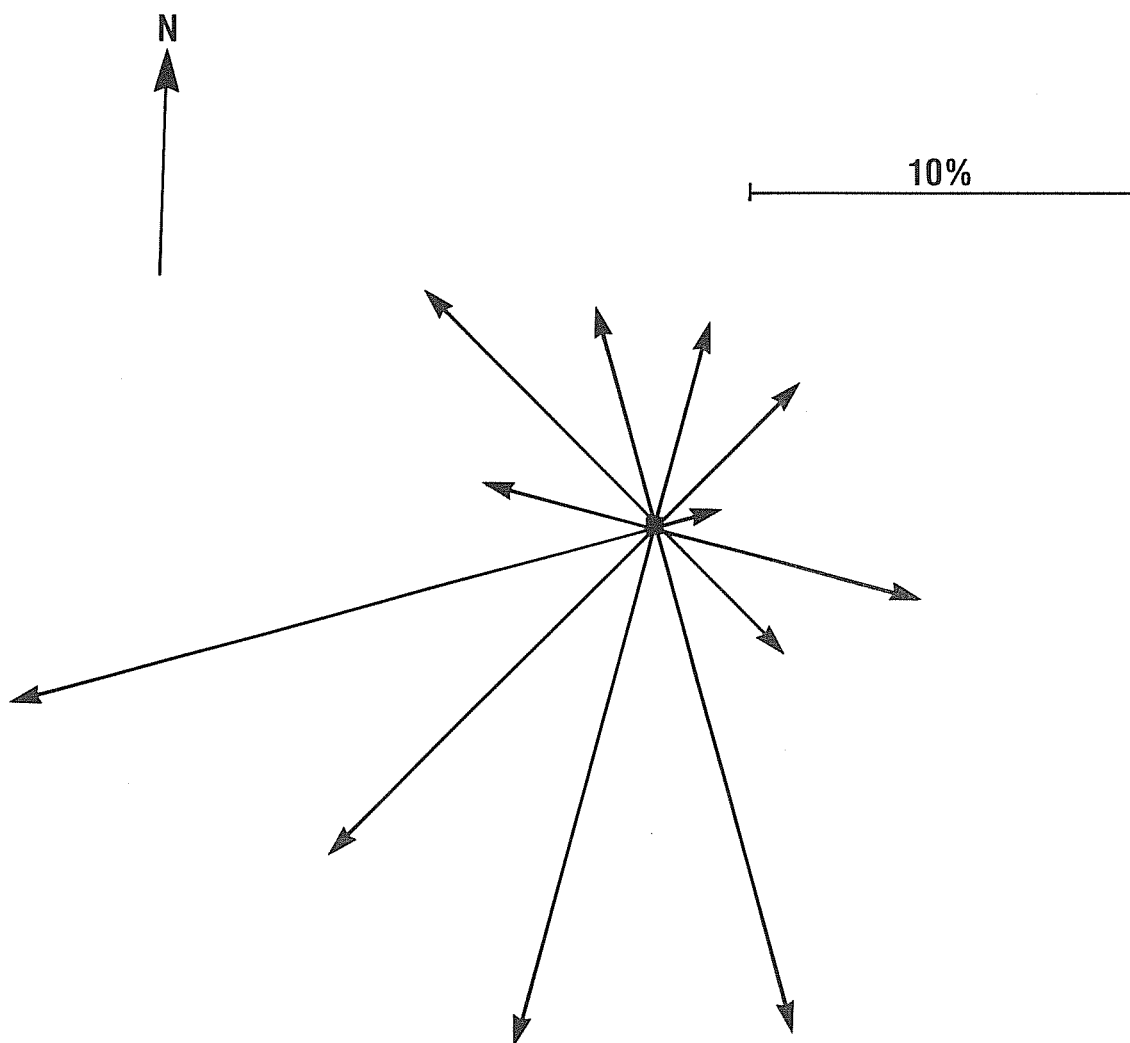


Figure 10

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QUESTIONS AND ANSWERS

JIM RAY (Shell): Bob, you said right toward the end the total chromium was 1.4 tons. Was that chrome or was that chrome lignosulfonate?

AYERS: That is chromium. I think it is 45 tons of chrome lignosulfonate.

JOHN DAVIS (Fisheries and Oceans, Canada): Bob, could you give us some details on the trace metal analysis? Were you running replicates, and did you ever try using several laboratories as a sort of cross calibration?

AYERS: The metals analyses were done at two laboratories, one laboratory in Houston where they used a total digestion procedure and these were the higher values.

Some I did not show you that are in the paper were acid leaching values done at the University of Delaware where some of the values were lower. The total digestion procedure used perchloric and nitric acid. We also used neutron activation for barium.

DAVIS: We found it extremely important to use at least two labs and to make sure you get a good cross-calibration in this type of study.

AYERS: We have experienced that, too.

DON WALTER (NOAA): Bob, you mentioned in the summary that there were two plumes that formed. Can you give a reason why. Were those plumes, one due to heavies and the other due to lights?

AYERS: No, I was trying to save some time by referring to what we discussed yesterday. What we noted in these discharge studies was that there are two basic plumes that form. You can think of it as a two-plume model where you have a plume that contains the bulk of the solids that descends rapidly and another plume that is formed by the turbulent mixing of the seawater with this plume as it descends that forms this upper plume, the visible plume.

Yesterday in the work we presented we estimated the maximum solids content of the upper plume to be between 5 and 7 percent of the total solids discharged, and so the bulk of the material goes down quickly. That is what we saw here, and this is the first time that we were able to get a diver sample of the lower plume very far down, 24 meters. It is always too low to sample with the helicopter. It falls too fast.

WALTER: So, the upper plume stayed above the thermocline?

AYERS: Yes, the upper plume is influenced by the thermocline. It is what we saw. Again, I am talking about what we determined in our other study we talked about yesterday. It does not interfere with solids settling, but it does suspend the colloidal solids that settle at extremely slow rates, and so the visible plume does follow the thermocline.

WALTER: Could you tell if there was any sheer associated with the upper plume, created by current changes or any other --

AYERS: In this case there was, especially during the 500 barrel per hour test. We did see toward the end of it a strong flattening. We had a current at 10 meters that was about 22 centimeters per second and one at the surface that may have been 5, and we had some strange things happen toward the end of the 500 barrel per hour test.

JACK THOMPSON (Texas A&M): Bob, do you have any feel for what sort of discharge rate it requires to create this two-plume situation?

AYERS: I think if discharge very, very slowly you are less likely to have it. I cannot be quantitative about it.

BOESH: I just have one comment in that regard. It may be wise to look at experience in other areas, particularly dredge material disposal. There have been some recent developments in terms of models and understanding of what happens to this rapidly sinking plume and the fluid mud behavior once it is on the bottom.

AYERS: You may recall Maynard Brandsma's paper is an effort to build a dispersion model to predict that and the model was originally designed for dredged material.